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Renewable ocean energy in the Western Indian Ocean

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A B S T R A C T

Several African countries in the Western Indian Ocean (WIO) endure insufficiencies in the power sector, including both generation and distribution. One important step towards increasing energy security and availability is to intensify the use of renewable energy sources. The access to cost-efficient hydropower is low in coastal and island regions and combinations of different renewable energy sources will play an increasingly important role. In this study the physical preconditions for renewable ocean energy are investigated, considering the specific context of the WIO countries. Global-level resource assessments and oceanographic literature and data have been compiled in an analysis of the match between technology-specific requirements for ocean energy technologies (wave power, ocean thermal energy conversion (OTEC), tidal barrages, tidal current turbines, and ocean current power) and the physical resources in 13 WIO regions Kenya, Seychelles, Northern Tanzania and Zanzibar, Southern Tanzania, Comoros and Mayotte, Northern-, Central-, and Southern Mozambique, Western-, Eastern-, and Southern Madagascar, Réunion, and Mauritius. The results show high potential for wave power over vast coastal stretches in southern parts of the WIO and high potential for OTEC at specific locations in Mozambique, Comoros, Réunion, and Mauritius. The potential for tidal power and ocean current power is more restricted but may be of interest at some locations. The findings are discussed in relation to currently used electricity sources and the potential for solar photovoltaic and wind power. Temporal variations in resource intensity as well as the differences between small-scale and large-scale applications are considered.

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1. Introduction

Electricity demand is growing rapidly in East Africa and in the coastal states of the Western Indian Ocean (WIO). Due to insufficient developments in the power sectors the majority of the people have poor access to modern energy, and the WIO is one of the least electrified parts of the world [1,2]. Mainland WIO countries (Kenya, Tanzania, Mozambique) and Madagascar all have electrification levels below 20% at the national level, and from 1 to 11% in rural areas (data from 2003 to 2004) [3]. Domestic generation capacity is low, and energy system losses are high [1]. Electric grid extension is extraordinarily costly because of underdeveloped infrastructure and scattered populations; remote areas are often left out of reach. Decentralized grids based on thermal generators is a proven solution for rural areas, but diesel import and logistics make the systems costly and unreliable [4]. In contrast to the mainland WIO countries, the islands (Seychelles, Comoros and Mayotte, Réunion, and Mauritius) have comprehensive electric grid coverage but suffer from sparse domestic energy supply and a heavy dependence on imported fossil fuel [5].

Given the underdeveloped state of electricity grids, the long distances, and water barriers there is no 'one-fits-all' solution of energy supply in the WIO. More likely, future energy systems—from regional backbones to small, decentralized grids—will be based on a mixture of sources. To meet the challenges of the imminent African energy crisis a forceful drive for renewable energy sources (RES) has been suggested [6,7] and doubtless the abundance of unexploited RES (hydro, solar, biomass, geothermal, and to some extent wind) is high [7,8]. Hydropower may be the most promising power source in many areas, but its potency is reduced in coastal lowlands and islands. However, proximity to the ocean may provide other, still unrealized, energy opportunities in terms of ocean energy.

Ocean energy (wave power, tidal power, ocean current power, ocean thermal energy conversion (OTEC), oceanic bioconversion, and salinity gradient energy) comprises the least investigated RES in the WIO, only examined in one scientific study on tidal power in Tanzania [9] and locally confined resource assessments at the French island of Réunion, where ocean energy is part of the long-term energy planning [10]. Despite the lack of resource assessments WIO governments and research institutes have already been approached by ocean energy companies [11,12]. And a micro turbine have been deployed in a local initiative [13][1] .

Globally, ocean energy is being increasingly recognized [14,15] also in parts of the Indian Ocean. Tidal power and OTEC [16] have been deployed in India and evaluations of wave power and ocean current power are taking place in South Africa. Various ocean energy sources have been discussed and assessed for use in the Persian Gulf and the Gulf of Oman [17–19], indicating a potential for tidal and wave power [18]. On the opposite shore of the ocean extensive resources of wave energy have been identified in Australia [20]. As for western Africa, extensive potential for OTEC and oceanic bioconversion was claimed in a study from 1983 [21]. In spring 2011, a first wave power device, designed particularly for remote area conditions, was tested in Cape Verde [11]. Not only electricity but also desalination of seawater has been the driver for addressing ocean energy in the developing country context [11,16,22].

From the standpoint of growing electricity demand and ambitions for increased use of domestic and renewable energy sources, this study takes on a first comprehensive investigation of ocean energy resources in the WIO. Literature-based criteria of resource requirements have been used in an analysis based on existing oceanographic data. The findings are summarized for each region of the WIO, the match with other continuous renewable energy sources are investigated, and the results are discussed in terms of usefulness for national and decentralized grids.

2. Included ocean energy technologies and resource assessment criteria

Due to an historical competition with fossil-based energy most ocean energy technologies are still at a pre-commercial stage although some of the basic concepts were developed almost a century ago. Currently there is a great variety of concepts that have not yet been tested at full scale [23,24]. However, political drivers and extensive research and development have now triggered high expectations of a technology take-off within the next decade [15,25,26]. Esteban and Leary [15] applied a conservative and an aggressive scenario and predicted that the ocean energy contribution to the world electricity production by 2050 will be 1.7% and 9.8%, respectively. The first ocean energy CDM-project (Clean Development Mechanism for reduction of greenhouse gases) was registered in 2006 by South Korea [27]. Ocean energy plants have been built in India and several projects are underway in other developing countries [16,23,28].

It has further been suggested that a first important niche market for some ocean energy concepts will be 'remote islands', where electricity costs are high and incentives for self-subsistence are strong [29,30]. Importantly, not only remote islands but also rural areas of larger developing countries have elevated electricity costs due to expensive fossil fuel based thermal generation. For example, the Tanzanian standardized purchase tariff for electricity produced and sold to decentralized grids is three times higher (US¢ 25 kWh^{-1}, 2011) than for electricity sold to the main grid [31,32].

This study focuses on available resources in the WIO for the most commonly discussed ocean energy technologies: wave power, OTEC, tidal barrages, tidal current turbines, and ocean current power. Two levels of resource-based potential were used to categorize results: *high* (physical conditions clearly meeting or exceeding the general requirements for the technology) and *conditional* (physical conditions at the lower end of general requirements). The applied criteria are compiled in Table 1.

Most RES imply more or less intermittent power generation, and the nature of these variations influences the quality of the resource. The ocean energy sources considered in this study have temporal variations ranging from hourly to seasonal. The predictability of

[1] A very small tidal current turbine was deployed by local fishermen and researchers in central Mozambique in order to run a fish freezer—to the knowledge of the authors this is the first ocean energy converter in the region.

Table 1
Categories and criteria applied in this study of ocean energy resources in the Western Indian Ocean. Temporal variability, predictability, and ranking criteria refer to annual means if not specified otherwise.

	Wave power	OTEC	Tidal barrages	Tidal current turbines	Ocean current power	Solar PV	Wind power
Temporal variability	Daily & seasonal	Seasonal	Hourly & weekly	Hourly & weekly	Seasonal	Hourly & seasonal	Hourly & seasonal
Predictability	Moderate	High	High	High	High	Moderate	Low
Ranking criteria							
High	≥ 25 kWm^{-1}	≥ 20 ΔT, ≤ 5 km	≥ 5 m mean tidal range	≥ 2 m s^{-1} peak speed	≥ 1.5 m s^{-1} seasonal average speed	≥ 5.5 kWh m^{-2} d^{-1}	≥ 5.5 m s^{-1}
Conditional	15–25 kWm^{-1}	≥ 20 ΔT, ≤ 10 km	2.4–5 m mean tidal range	≥ 1.5 m s^{-1} peak speed	1–1.5 m s^{-1} seasonal average speed	3–5.5 kWhm^{-2} d^{-1}	4–5.5 m s^{-1}

these variations—that is, the certainty in forecasting energy availability over time—was ranked into *low* (not predictable from one day to the next), *moderate* (essentially predictable over days), or *high* (essentially predictable over years).

2.1. Wave power

Wave power devices convert energy from wind driven surface waves to electricity. As the energy in waves dissipates slowly it can be carried over long distances and reach shores far beyond its origin. The global distribution of wave energy reflects the wind patterns, with most energy bound to western-facing coasts at high latitudes and eastern-facing shores at low latitudes [33]. As the energy originates from wind, the wave energy resource is variable and undergoes both seasonal and daily changes [34]. However, swell (long wavelength waves), which characterizes wave patterns at low latitudes, evens out much of the short-term variation. Wave power is more predictable and less variable than wind power [33].

Wave energy is extracted by using the motion of water to spin turbines or drag linear generators. Currently, more than 80 different technical concepts are under development [23]. Some devices are made to operate as floating arrays in deeper coastal water; others will be moored to the bottom in the shallows, or installed as wave breakers on the shore. While shore-based wave power plants are large, floating devices often consists of small units (20–1000 kW). As the frequency spectra of waves differs between sites, the bandwidth of a device can be regulated to tune it to particular waves or to keep efficiency adequate over a wider range of wave conditions [35]. The latter, generalist, approach may be advantageous in small-scale applications where less site-specific background information is available.

Most projected installations of wave power concern large arrays with hundreds or thousands of units, but being based on small units several devices may also be suitable for small-scale deployment. Interesting examples of small-scale options are the Cape Verde device developed by Euro Wave Energy [11] and the SAS-2 converter presented by Ayub et al. [36]. Both of these converters have shore-based generators, a robust design, and are promoted for developing countries, including remote community electrification and the production of potable water (desalination).

At the basic level, wave power potential is measured in terms of energy density per wave crest (kW m^{-1}). Current technologies harvest about one fifth of the available resource, but numbers differ between conditions and devices. Since the required energy density varies between devices, it is not straightforward to determine generic resource criteria for wave power potential. Based on [23], wave power devices are typically optimized for 15–35 kW m^{-1}; and 20 kW m^{-1} has been regarded a good potential [34,37].

In this study, where assessment is based on deep water wave energy, the criterion for high potential was set to 25 kW m^{-1} wave crest and the criterion for conditional potential was set to 15 kW m^{-1}. These criteria are conservative and it should be noted also that also lower levels of energy density may become economic as long as the utility factor is high [38]. For example, wave power levels below 15 kW m^{-1} have been considered suitable for desalination and irrigation [22]. Furthermore, the occurrence of extreme waves must be considered [39] as many wave power systems are relatively small. It is likely that floating devices would take serious damage from strong tropical cyclones, which are known to cause extensive damage on coastal infrastructure [40,41].

The knowledge on environmental impacts from wave power is scarce [42] and several potential impacts have been suggested [43]. Still, the magnitude of possible detrimental effects is likely to be limited [44].

2.2. OTEC

OTEC technology utilizes the temperature difference between cold deep water and warm surface water of tropical oceans, which is converted to electricity through heat-exchange principles. The potential of this resource is huge and most pronounced in ocean areas with high temperature differences (ΔT). The highest ΔTs are found in the western Pacific, but adequate ΔT exists in most tropical seas [45]. The power output from OTEC undergoes predictable seasonal variations, associated with the global oceanic circulation.

OTEC technology has been explored for more than a century, but low efficiency and complicated engineering requirements have delayed widespread implementation [33,46]. Three different OTEC principles have been in focus: open-cycle systems, closed-cycle systems, and hybrid systems. Large intake pipes are used to pump warm water from the surface layer and cold water from the depth. The open-cycle system vaporizes the warm water in low-pressure chambers and leads the steam through large diameter turbines. The cold water is used to re-condense the vapour which can be separated into useful fresh water and saline condensate [47,48]. The closed-cycle system involves a secondary working fluid, which is vaporized, re-condensed, and recycled. Typical working fluids are ammonia or propane, but other suitable fluids are also being considered in order to enhance efficiency [46]. Another proposed way of greatly improving the efficiency of OTEC plants is to use solar thermal collectors or sun-heated basins to boost the temperature of the inflowing surface water before it reaches the heat exchanger [49,50]. Such solar-boosted OTEC implies some diurnal variation in efficiency and power output.

Commercial-scale OTEC plants will have a capacity of 10–100 MW and will operate from shore-based facilities, moored platforms, or mobile craft. The shore-based approach implies facilitated logistics and huge power transmission advantages but the number of potential sites becomes limited by the distance between land and deep water; for the cold water intake pipe to be

of feasible length the continental shelf must be very narrow. The required ΔT for OTEC to operate adequately is about 20 °C [15,51], but the higher the ΔT, the higher the potential. The surface temperature of tropical oceans is around 25–30 °C and it is generally assumed that cold enough water is found at 1000 m depth (however, in certain areas it may be found less deep). For land-based systems, cold water must be found within accessible distance from shore. A maximum distance of 25 km from land has often been used as an initial localization criterion [15,47,52], but pipe length is an important economic factor, and shorter distances are much preferable. Based on [53,54] distances of 5 and 10 km from shore to a ΔT of 20 °C were applied as the criteria for high and conditional potential, respectively (only land-based OTEC was considered).

Other physical criteria for OTEC are related to slope, bottom substrate, allowing safe mooring, and ocean currents that must cater for an efficient removal of discharge water since all OTEC systems imply large quantities of discharge water with altered temperatures that may influence surrounding ecosystems.

2.3. Tidal barrages

Tidal barrages utilize the potential energy of tidal elevations. The gravitational forces of the moon, the sun, and the centrifugal forces of the rotation of Earth, affect the oceans and give rise to global tidal waves. The tidal waves follow a predictable pattern where the tide rises (flood) and falls (ebb) once (diurnal tides) or twice per day (semidiurnal tides). In addition, the magnitude of tidal waves is increased twice per month, resulting in stronger spring tides and weaker neap tides. To a lesser degree, weather conditions also affect the magnitude of tides. Although the tidal range is low in the open ocean it can be greatly amplified by the position of landmasses and ocean bathymetry such as gently rising slopes [55].

As tides are highly predictable, the output from tidal power can be determined in advance with only small weather-induced deviations. Nevertheless, the hourly and weekly variation, with periods that are not in tune with human consumption patterns, is a drawback for tidal power.

The principle of tidal barrages is to trap a fraction of the tide and keep it out of phase with the natural tide, hereby creating a difference in water level (head) between the enclosed water and the sea. The water levels are allowed to even out by passing through low head turbines. Power can be generated during ebb (one-way operation) or during both ebb and flood (two-way operation) [56]. In the case of one-way operation the basin is filled up through open gates during flood and water is let out through turbines when the receding ebb has created a sufficient head (H_{min}). Two-way operation means that water is directed through turbines during both flood and ebb, and more power can be generated. By power plant design (e.g. adjustment of H_{min} and flow rate) a tidal barrage can be optimized with respect either to maximum energy output or to power availability over time, the latter of particular importance in small electric grids.

A few tidal barrages have been operating in Canada, France, Russia, and China for many decades. In recent years, a renewed interest in tidal barrages has led to new suggested projects. Some examples are the Republic of Korea, the UK, Mexico [23], Brazil [57], and India [29]. Tidal barrages are applicable at a wide range of scales: large impoundments include planned mega projects up to thousands of km^2 [58] but small barrage designs, which imply easier construction work and a less severe manipulation of the natural tidal regime, have also been found feasible [59,60]. For example, small tidal barrages and decentralized electricity grids have been used to supply agriculture in China [30,61]. Even micro-scale tidal barrages, with removable barriers deployed in small tidal ponds, have been proposed as an inexpensive alternative for remote area electrification [33]. Parallels can be drawn to pico-hydro systems (<5 kW) which have been shown to be successful and inexpensive for decentralized electrification in e.g. Kenya [62].

Traditionally it has been assumed that a mean tidal range of at least 5 m is necessary for tidal barrages to be economically viable [63]. Yet, the Russian Kislaya and Chinese Baishakou tidal barrage power plants have been operating in 2.4 m mean range for many decades, e.g. [64]. Modern low-head turbines, with high efficiency even below 2 m head, can be used for tidal barrages in relatively low tides [33,65,66] and it has been argued that the potential of tidal barrages are often overlooked [67]. In this study, mean tidal ranges of 5 m and 2.4 m have been applied as the criteria for high and conditional potential, respectively. However, also lower tides may be sufficient for micro-scale tidal barrages, as indicated by the historically large number of tidal mills in areas with limited tidal ranges in western Europe and America [68]. The feasibility of a tidal barrage is practically determined by the energy output in relation to the installation cost, in turn largely dependent on the length and configuration of the barrage [63]. Natural impoundments therefore reduce installation costs. Moreover, stable sediment is required for mooring, and the sedimentation rate should be low in order to minimize the need of maintenance dredging.

All barrage systems will change the tidal regime and thus affect the intertidal flora and fauna [69–71], bringing changes that may affect ecosystem structure and function, and thus indirectly fisheries.

2.4. Tidal current turbines

Tidal current turbines generate electricity from the kinetic energy of fast-flowing tidal currents that develop from tidal movements around peninsulas or through narrow sounds. Both tidal amplitude and bathymetric geometry have a major influence on the current speed. Based on measurements, site-specific current patterns can be modeled on the basis of generic tidal constituents [72]. As with tidal barrages, the power generation from tidal current turbines is highly predictable but varies over hours and weeks, out of phase with human consumption patterns.

The conversion principle varies between the about 40 tidal current turbines designs currently in development. Some devices are based on hydrofoils but more commonly horizontal or vertical turbines are driven by rotors much like wind power turbines. The device may be submerged and fixed to the bottom or anchored and floating at the surface. The power capacity ranges from 10 kW to 5 MW per unit. A few full-scale devices have been deployed [23]. Large-scale tidal farms comprise tens to hundreds of units in fast flowing currents (>2 m s^{-1}) and water depths above 20 m. These conditions require heavy foundations and weights of up to hundreds of tons per device [24]. The large dimensions and complicated installations imply a focus on large sites in proximity to infrastructure facilities. Concurrently, some devices with simplified installation and maintenance have been promoted for small-scale employment [73]. With low cut-in speed and high generator efficiency at low speed, light devices can operate in less harsh sites. However, the energy content in water depends on the cube of its velocity and the power output quickly decreases as currents slow down.

Tidal current turbines require far less modification of the natural tidal regime than barrages but, conversely, do not offer any solutions for evening out power generation over time. It is generally assumed that a spring current speed of 2–2.5 m s^{-1} is required for tidal current turbines to be economically feasible [18,23,64]. There are technical solutions to increase the water speed over the rotor and tidal power resource screenings have

considered currents down to 1 m s^{-1} [74]. In this study, 2 m s^{-1} has been applied as the criterion for high potential whilst 1.5 m s^{-1} was used to indicate conditional potential. As current speed is highly site-specific in coastal waters, categorization of the resource is restricted to the specific area where measurements were taken unless bathymetry is fully known.

Similarly to wave power devices, floating tidal current turbines can be considered fragile in respect to extreme weather such as tropical cyclones. The environmental impact of tidal current turbines is not well known [71,75].

2.5. Ocean current power

Ocean current power operates under similar principles as tidal current turbines but utilizes the more persistent oceanic currents instead of tides. Hence power output is highly predictable and varies on seasonal rather than a daily basis. Oceanic currents primarily emerge from the Earth's rotation and are strongest in western parts of the oceans. Although the mass transport of oceanic currents is immense, the energy density is generally low due to low velocities. One of the most powerful ocean current systems in the world is the Somali-Agulhas system which stretches along the East African coast [33].

Over the past fifty years, there have been numerous innovations suggested for the extraction of energy from the large ocean currents. In order to make use of slow currents, the actual flow over the rotor has to be enhanced. This problem has been approached by various designs where the most common has been to construct a ducted shroud over the turbine. The water is dragged through the turbine due to the pressure gradient that develops from the shape of the duct, increasing the flow velocity and improving the conversion efficiency of the device. Previous innovations for ocean current power has been of huge dimensions (with units measuring up to 150 m in diameter [33]). A recent approach, which is based on 220–500 kW units measuring 12 m in diameter, is the Deep Green prototype [76]. In this concept, the turbine is mounted on an anchored submerged "kite" that circulates with the current and amplifies the experienced water speed over the rotor by a factor of ten, according to the developer. The Deep Green targets current velocities from 1 m s^{-1}, which means that the number of potential sites increases in comparison to other ocean current power technologies. Another ocean current power technology under development is the Florida Hydro which measures 45 m in diameter and produces 2–3 MW per unit [77]. Regardless of the technology used, only large-scale projects are likely to be commissioned since ocean currents are associated with rough offshore conditions and expensive power transmission.

In this study, the criteria for high and conditional potential for ocean current power were set to seasonal average coastal current speeds of 1.5 and 1 m s^{-1}, respectively. However, as the technology has not been tested at full scale any assessment is associated with high uncertainties. Similarly the possible environmental impacts are not known.

2.6. Land-based RES

Insolation and wind energy are examples of RES that can complement ocean energy although coastal cloudiness may reduce the insolation and coastal wind is not as prominent in the tropics as in high latitudes, due to low difference between land and sea temperature. The technical development of solar photovoltaic (PV) and wind power is far beyond that of ocean energy and the resource distribution is well known at a coarse level. This study examines how coastal solar and wind resources match with ocean energy. Tanzanian energy tariffs [31,32] for electricity sold to main-grid and off-grid systems (including feed-in tariffs based on diesel costs) were the basis for approximated resource criteria. The criteria for high and conditional potential for solar PV were set to insolation levels of 5.5 kWh m^{-2} d^{-1} and 3 kWh m^{-2} d^{-1}. For wind power, average speeds of 5.5 m s^{-1} and 4 m s^{-1} (at 10 m height) were used.

3. Methods

The resource-based potential and other physical preconditions for each technology in each studied region were assembled from oceanographic literature, databases, and global-level resource assessments. Some of the data were compiled in a previous thesis [78].

3.1. Study region

The regions of this case-study is depicted in Fig. 1, based on [79]. The WIO was separated into 13 regions in order to facilitate the analysis of results: Kenya, Seychelles, Tanzania–Zanzibar, Southern Tanzania, Comoros and Mayotte, Northern Mozambique, Central Mozambique, Southern Mozambique, Western Madagascar, Eastern Madagascar, Southern Madagascar, Réunion, and Mauritius.

The WIO has a tropical to sub-tropical climate with water surface temperatures between 20 and 30 °C and air temperatures rarely falling below 20 °C. The climate is strongly affected by monsoons, where the northern monsoon generates light steady winds of 5 m s^{-1} from November to March and the southern monsoon generates stronger winds (up to averages of 9 m s^{-1} in southern parts of the region) from June to September [80]. The monsoon wind patterns influence the seasonal configuration of waves and ocean currents. In this study, extended monsoon periods have been used as the reference for analysis of seasonal differences, where the northern monsoon includes November–April and the southern monsoon includes May–October.

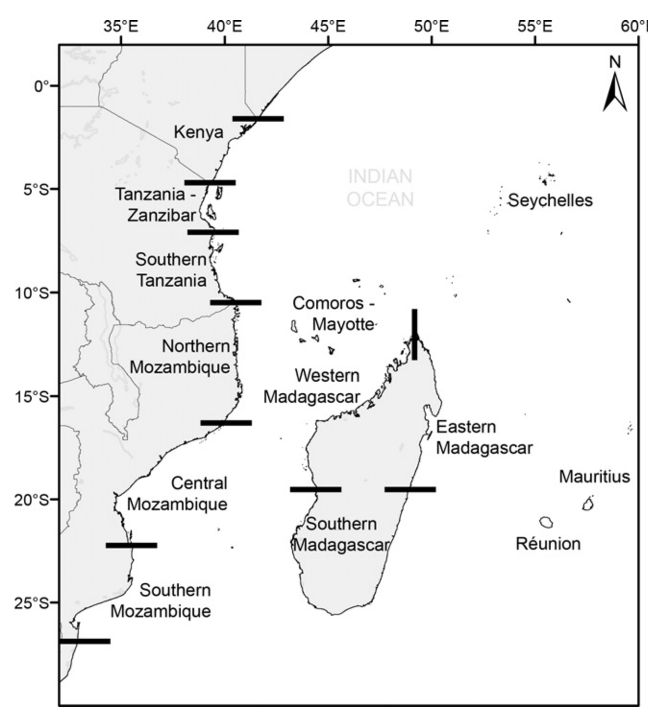

Fig. 1. Map showing the investigated part of the Western Indian Ocean and the 13 assessed regions (indicated by their name).

Table 2
Key geophysical conditions [80] and landfall periodicity of tropical cyclones based on the period 1980–2009 [81]. Cyclone periodicity refers to the average number of years between cyclones that reach the coast of each region; it is not a measure on cyclone frequency at a given location. Oceanic currents are labeled as EACC (East African coastal current), SEC (south equatorial current), ECC (equatorial counter current), MoC (Mozambique current), and MaC (Madagascar current).

Region	Typical coastal morphology	Shelf bathymetry	Dominant ocean current	Landfall periodicity of cyclones (years)
Kenya	Limestone	Variable	EACC	–
Seychelles	Limestone, granite	Variable	ECC	20
Tanzania–Zanzibar	Limestone	Variable	EACC	–
Southern Tanzania	Limestone	Narrow shelf	EACC	30
Comoros and Mayotte	Volcanic rock	Narrow shelf	MoC	3
Northern Mozambique	Limestone	Narrow shelf	MoC	3
Central Mozambique	Estuarine and sand	Shallow	MoC	2
Southern Mozambique	Sand	Shallow	MoC	10
Western Madagascar	Estuarine and rock	Variable	MoC	1
Eastern Madagascar	Sand and rock	Narrow shelf	SEC	1
Southern Madagascar	Sand and rock	Narrow shelf	MaC	1
Réunion	Volcanic rock	Narrow shelf	–	1.5
Mauritius	Volcanic rock	Narrow shelf	–	2

Southern WIO experiences recurrent tropical cyclones with powerful and potentially devastating impacts on coastal areas. Tropical cyclones appear during the northern monsoon with peak occurrence in January–March, most frequently exposing Madagascar, Réunion and Mauritius, Mozambique, and the Comoros [81].

The geological history of the WIO originates from the break-up of Gondwanaland including Madagascar's drift with respect to continental Africa, the formation of the Indian Ocean marginal basins [82]. A steep continental shelf was formed. Coastal features are typically dominated by Pre-Cambrian rock, volcanic rock, fossil coral limestone, and estuarine coastal plains [80]. These geophysical conditions, compiled in Table 2, are important for the feasibility of different technologies.

3.2. Wave power

The energy flux P in surface waves can be calculated from the wave height and the wave period according to Eq. (1):

$$P = \frac{\rho g^2}{64\pi} H^2 T \tag{1}$$

where ρ is the water density (kg m^{-3}), H is the significant wave height (m), and T is the wave period (s). The unit is kW m^{-1} that represents the power per meter of wave crest. The expression is restricted to surface waves in water deeper than half the wavelength.

The first screenings of wave power resources relied on visual observations from maritime reports. Obviously, the method is rather qualitative but has been defended by the assumption that visual observations generally tend to underestimate rather than overestimate the significant wave height [83]. Modern methods are based on altimetry, with height and period of waves determined from remote-sensing observations and calibrations using buoy measurements. Two drawbacks of remote sensing methods are inaccuracy in near-shore waters [84,85] and difficulties in fully accounting for the energy in ocean swell [84].

In this study, global-level wave power assessments generated from visual observations [83] and altimetry-based models [39] were used. Quayle and Changler [83] calculated annual means of wave power from an extensive global database of marine vessels reports from 1971 to 81, calibrated by a wave climate database. Barstow et al. [39] presented annual and seasonal means of wave power, and the outcome of extreme waves, based on ten years of altimetry data calibrated by buoy measurements. A comparison of the two data sources showed that the altimetry data [39] with higher spatial and temporal resolution generated the more conservative estimates for the WIO coast. This source was hence used as the primary source. For illustration purposes (Fig. 2), inverse distance weighted interpolation (IDW), based on two neighboring values and a spatial resolution of one degree, was performed in ArcGIS to generate data for each intersection of the coast. As data were based on deep-water conditions the actual wave power at the shore will be reduced [85]. Based on [86] this reduction of wave power would be <10%. However, site-specific investigations are needed for detailed resource assessments.

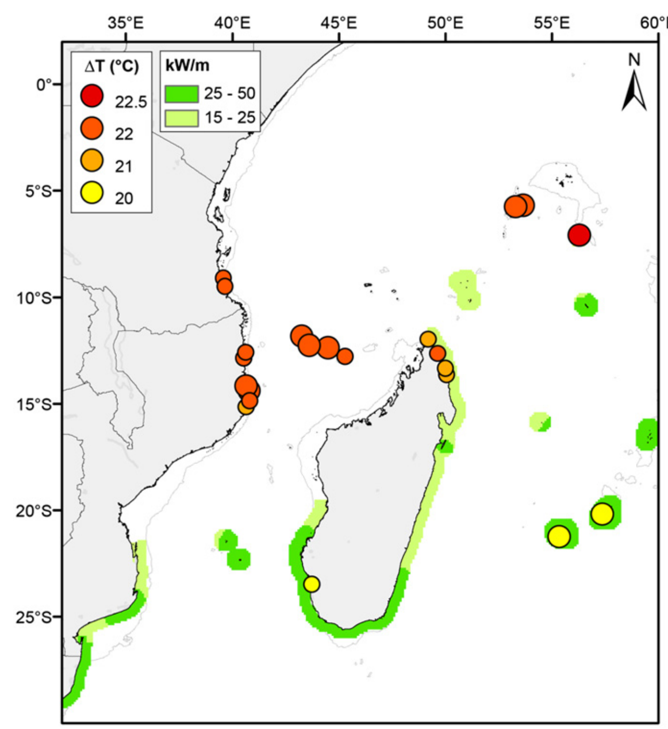

Fig. 2. Distribution of wave power and OTEC resources in the WIO. Green areas indicate annual mean wave power (kW m^{-1}) for coastal deep-water conditions. Circles mark locations with $\Delta T \geq 20$ °C within 5 km (large circles) and 10 km (small circles) from shore. Isoclines indicate 1000 m depth. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.3. OTEC

Several studies have addressed the global level resource potential for OTEC based on the ΔT and bathymetry [33,45,48,51]. None of these studies have provided detailed descriptions of the OTEC potential in the WIO, so bathymetry and temperature data acquired from the African Marine Atlas [87] were used to examine the OTEC-related conditions in the WIO: shoreline contour [88], 1000 m depth contour [89], and ocean temperatures [90], for each increment of the coast. The distance from shore to 1000 m depth was calculated in ArcGIS. The annual means of ΔT were extracted for all coastal locations found within 10 km distance from the 1000 m depth. Global-level maps of ΔT for February and August [91] were used for an overview of seasonal variations.

3.4. Tidal barrages

The tidal range at WIO locations was compiled from oceanographic literature [92–96]. To assess the potential at criteria-meeting locations, the energy output (per km^2) was calculated for different barrage designs. A basic semidiurnal tidal model (Eq. (2)), based on a daily period of 12 h 25 min and a monthly period of 14.75 days [64], was used to calculate the tidal fluctuations at each location:

$$Z = SR\cos\left(2\pi\frac{t}{T_1}\right) \quad \left[A - B\cos\left(2\pi\frac{t}{T_2}\right)\right],$$
$$A = 1 - \frac{(SR-NR)}{(2SR)}, \quad B = \frac{(SR-NR)}{2SR} \tag{2}$$

where Z is the tidal level, SR is the spring range (average range during peak spring), NR is the neap range (average range during full neap), T_1 is the daily period and T_2 is the monthly period.

The tidal model (Eq. (2)) was calibrated for each criteria-meeting location and SR and NR were estimated from tidal tables (March–June 2010) [95]. No corresponding data were available for the Nosy Chesterfield location (Madagascar), instead SR and NR were estimated based on locations with equivalent mean tidal range: Moçimboa da Praia and Quelimane (Mozambique).

Eq. (3) describes the electric energy E_e of a tidal barrage:

$$E_e = c_p\frac{\rho g A H^2}{2}, \quad H \geq H_{\min} \tag{3}$$

where c_p is the conversion efficiency, ρ is the density of sea water (kg m^{-3}), g is the gravitational force (m s^{-2}), A is the intake area of turbines (m^2), H is the difference (m) between the water levels inside and outside the basin. Eqs. (2) and (3) were combined to calculate the potential energy output and power availability over time for tidal barrages using (i) one-way operation mode, and (ii) two-way operation mode. H_{min} and the flow rate through turbines were optimized for maximum energy output [56]. Energy output was calculated in MATLAB® assuming a conversion efficiency of 0.75 and a constant basin depth.

3.5. Tidal current turbines

To the knowledge of the authors there has been no large-scale modeling of tidal currents in the WIO. However, site-specific information of tidal current velocities at various locations was compiled from literature [9,93,97–100] and unpublished data [101]. The observation specifically referring to bottom current speed the mid-water current speed was calculated using the 10th power law for turbulent flow [102].

Quantitative estimates of the theoretical resource were not achievable due to a lack of site-specific information on bathymetry and exact positioning of measurements. Instead, the potential energy output was calculated for specific tidal current turbines (small or micro). Most of the compiled data were restricted to measurements or estimations of maximum speed. Therefore, a semidiurnal tidal current model (Eq. (4)) was used to simulate the full tidal cycle. The model was modified from [72] by adding the ratio of ebb to flood currents (d_{fe}):

$$v = \begin{cases} MSS\cos\left(\frac{2\pi t}{T_1}\right)\left(1-\left(\frac{MSS-MNS}{2MSS}\right)\left(1+\cos\left(\frac{2\pi t}{T_2}\right)\right)\right) & nT_1 \leq t \leq \frac{(2n+1)T_1}{2} \\ -d_{fe}\left(MSS\cos\left(\frac{2\pi t}{T_1}\right)\left(1-\left(\frac{MSS-MNS}{2MSS}\right)\left(1+\cos\left(\frac{2\pi t}{T_2}\right)\right)\right)\right) & \frac{(2n+1)T_1}{2} < t < (n+1)T_1 \end{cases} \quad n = 1,2,3\ldots \tag{4}$$

where MSS is the maximum speed during peak spring and MNS is the maximum speed during full neap given as a proportion of MSS, t is time, T_1 is the period of the daily tidal cycle, and T_2 is the period of the monthly tidal cycle. Based on [24] and [74], the maximum speed from the different locations was assumed to represent MSS while the MNS was set to 0.6 MSS. The d_{fe} was set to 0.84 based on analysis of Mozambican tidal current data described in [98].

Eq. (5) describes the generated power P_e for a tidal current turbine:

$$P_e = 0.5 C_p \rho A v^3 \quad v \geq v_{cut-in} \tag{5}$$

where C_p is the conversion efficiency, ρ is the density of sea water (kg m^{-3}), and A is the area swept by the rotor (m^2). As the generator efficiency varies with current velocity and as different turbines have different performance the conversion efficiency of tidal turbines varies both with water speed and between devices. The water-to-wire conversion efficiency is typically estimated within the range of 0.35–0.5 for different devices [58,102,103]. Conservatively, the calculations in this study are based on C_p=0.35 throughout the tidal cycle. Energy output was calculated for two different size-classes of tidal current turbines[2] : (A) a small device based on the Verdant free flow kinetic hydropower system employed in the New York City's East River since 2006 [23,24]; and (B) a hypothetical micro-scale device corresponding to an anchored raft deployed with four Gorlov helical turbines.

3.6. Ocean current power

The WIO is well covered in oceanographic literature and the oceanic currents have been investigated by various methods. Still, there are no detailed mappings of coastal surface current velocities. Areas of particularly strong coastal currents were identified from [104,105], and were further investigated through a comprehensive set of historical ship drift data. These ship drift observations, originally obtained from the Meteorological Office of Historical Surface Currents, consist of non-filtered reports from 1854 to 1974 which were compiled by Cutler and Swallow [106] into means of determining current velocity with a geographical resolution of one degree (1°) quadrangles, and a temporal resolution of 36 periods from January to December (10-day means). Outliers (where both flow direction and speed strongly deviated from the prevailing current) were removed, and mean and maximum values were calculated for northern and southern monsoon periods. Finally, the data were interpolated (IDW) in ArcGIS for illustration purposes (Fig. 3).

Although there are obvious uncertainties associated with the use of historical ship drift data the influence from wind and navigation errors has been shown to be small in strong currents and can be neglected when large data sets are used [107].

[2] Applied technical assumptions: A (labeled "small" in Table 6); 36 kW rated power in 2.1 m s^{-1} current, 0.7 m s^{-1} cut-in speed, 20 m^2 swept rotor area, 6–20 m target depth; B (labeled "micro" in Table 6); 20 kW rated power in 2 m s^{-1} current, 0.5 m s^{-1} cut-in speed, 10 m^2 swept rotor area, 5 m minimum depth.

3.7. Current electricity supply and land-based RES

Information on currently used power sources was compiled from country-specific reports [1,108–113]. In order to put the ocean energy resources in the context of future energy systems, basic satellite generated data of insolation and wind speed were derived from the Atmospheric Science Data Center [114].

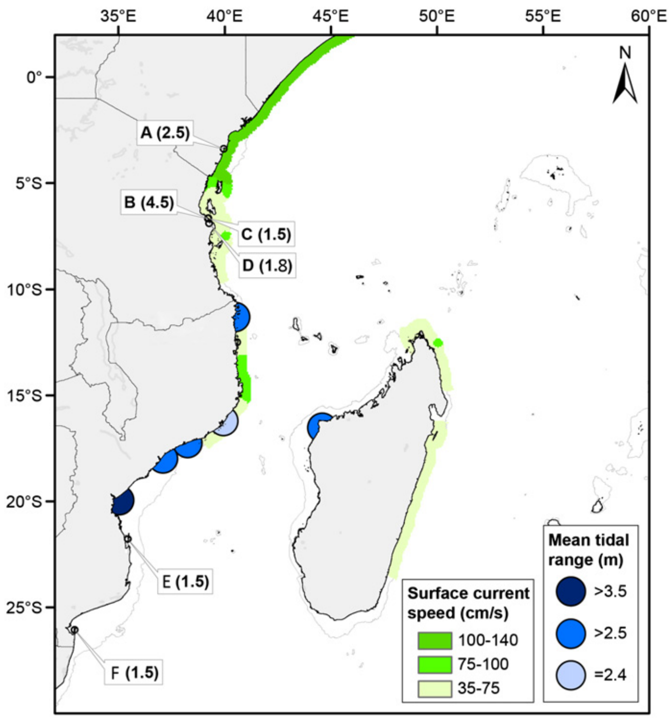

Fig. 3. Indications of tidal and ocean current resources in the WIO. Circles show mean tidal range at selected locations (mean tide ≥ 2.4 m). Labels indicate sites with tidal currents ≥ 1.5 m s^{-1} (mid-water maximum speed indicated, m s^{-1}) at locations: A—Watamu, B—Kunduchi, C—Mbudya, D—Dar es Salaam harbor, E—Bazaruto Island, F—Inhaca Island. Green areas indicate seasonal average surface speed (cm s^{-1}) of ocean currents, based on ship drift. Light gray isoclines indicate 1000 m depth. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Results and discussion

4.1. Wave power in the WIO

High potential for wave power (≥ 25 kW m^{-1}) was found throughout southern WIO, including Southern Mozambique, Southern Madagascar, Réunion, Mauritius, and parts of Eastern Madagascar. The wave power is highest in Southern Madagascar where the annual average reaches 50 kW m^{-1} (Fig. 2, Table 3). Most of Eastern Madagascar and a few islands of the Seychelles have a wave power potential rated as conditional (15–25 kW m^{-1}). The seasonal variation of wave power (the ratio of minimum individual monthly wave power to the annual average) is low in the southern hemisphere and throughout the WIO [34,39]. Still, there are differences between seasons, and the wave power is higher during the southern monsoon (southern hemisphere winter). During this period the wave power exceeds 15 kW m^{-1} in most of the WIO. Furthermore, analyses by Cornett [85] and Barstow et al. [39] showed that the frequency of destructive waves is low throughout most of the WIO (estimated as the ratio of the highest significant wave height to the average wave height).

There is no doubt that wave power resources allow for considerable energy extraction in the WIO, and if wave power technology becomes available, the resource may be of interest both for large-scale generation and for micro-scale applications for remote area electrification and desalination purposes. However, the occurrence of tropical cyclones in southern WIO is likely to restrict the number of suitable sites.

4.2. OTEC in the WIO

High potential for OTEC was indicated at 11 locations in the Seychelles, Northern Mozambique, the Comoros, Réunion, and Mauritius (Fig. 2, Table 4). Conditional OTEC potential was found in Southern Tanzania, and Eastern and Southern Madagascar. The locations with highest OTEC potential were the Comoros, Mozambican Nacala, and several islands in the Seychelles. According to the analysis, the ΔT averaged 22 °C within 3 km from the coast at these locations. The results are supported by the temperature measurements presented by Chapman [115] but has not been recognized in

Table 3
Deep-water wave power (kW m^{-1}) for selected coastal locations in the WIO, based on visual observations [83] and altimetry-based models [39]. The approximation of wave power regards depths > than half wavelength.

Region	Location	Visual observations	Altimetry-based modeling		
		Annual	Annual	January	July
Kenya	Kiunga	16	10–15	5–10	20–30
Seychelles	Seychelles	–	10–15	5–10	20–30
Seychelles	Coetivy Island	–	15–20	5–10	30–40
Tanzania Zanzibar	Zanzibar	12	5–10	< 5	15–20
Southern Tanzania	Lindi	14	5–10	< 5	10–15
Comoros and Mayotte	Comoros and Mayotte	12	5–10	5–10	10–15
Northern Mozambique	Nacala	14	10–15	5–10	15–20
Northern Mozambique	Quirimbas Archipelago	12	< 5	5–10	10–15
Central Mozambique	Beira	27	10–15	< 5	10–15
Central Mozambique	Quelimane	19	10–15	5–10	15–20
Southern Mozambique	Inhambane	34	20–30	15–20	30–40
Eastern Madagascar	Cape East	–	15–20	10–15	30–40
Western Madagascar	North-west coast	10	< 5	5–10	< 5
Southern Madagascar	Tolagnaro	–	40–60	30–40	40–60
Southern Madagascar	Androka	38	30–40	20–30	40–60
Southern Madagascar	Fenoambany	–	20–30	20–30	40–60
Southern Madagascar	Andavadoaka	18	20–30	10–15	30–40
Réunion	Réunion	–	20–30	15–20	30–40
Mauritius	Mauritius	–	30–40	20–30	40–60
Mauritius	Agalega	–	20–30	10–15	30–40

global-level assessments of OTEC potential [33,47,48]. Because of strong deep-sea currents, the seasonal variations of ΔT are relatively high in the WIO compared to other oceans [45]. Even at the most suitable locations ΔT dips to 19–20 °C during the Southern monsoon.

OTEC, particularly solar-boosted systems, may be a suitable power source for several regions of the WIO once the technology is fully developed, given the particular values of low variation and predictability of power generation from this energy source, which is indicated by the current OTEC ambitions in Reúnion [47,113]. It should be noted though, that the environmental impacts of OTEC are not fully known [116].

Table 4
Minimum distance between shore and 1000 m depth and annual mean temperature difference between surface water and deep water at 1000 m depth for locations in the WIO.

Region	Location	Distance (km)	ΔT (°C)
Seychelles	Desroches Island	2.5	22
Seychelles	Poivre Island	2.5	22
Seychelles	Coetivy Island	3	22.5
Southern Tanzania	Kilwa	7.5	22
Southern Tanzania	Lindi	9.3	22
Comoros and Mayotte	Grande Comore	2.1	22
Comoros and Mayotte	Anjouan	2.3	22
Comoros and Mayotte	Moheli	4.9	22
Comoros and Mayotte	Mayotte	5.7	22
Northern Mozambique	Nacala	2.8	22
Northern Mozambique	Memba	3.5	22
Northern Mozambique	Calajulo	5	21
Northern Mozambique	Matibane	5.7	22
Northern Mozambique	Pemba	7.6	22
Northern Mozambique	Quisiva Island	8	22
Eastern Madagascar	Andranovondronina	6	21
Eastern Madagascar	Masondrono	8.2	21
Eastern Madagascar	Ampondrabe	8.7	22
Eastern Madagascar	Vohemar	9.3	21
Southern Madagascar	St Augustin	8.4	20
Réunion	Réunion	1.8	20,5
Mauritius	Mauritius	1.3	20

4.3. Tidal barrages in the WIO

Because of the location of Madagascar, the oceanic tidal wave induces elevated tides over the East Africa continental coast and Western Madagascar (Fig. 3). The semidiurnal tides of Mozambique, Tanzania, Kenya, Comoros and Mayotte and Western Madagascar are classified as macro-tidal, defined by a spring tidal range above 3 m [94], and several locations have tides comparable to other areas where small-scale tidal barrages are operating or planned (e.g. China, Russia, and India). However, the mean tide does not reach 5 m at any location and thus the potential for tidal barrages has only been ranked as conditional (Central and Northern Mozambique and Western Madagascar). The inner parts of the Sofala Bank in Central Mozambique (Beira), where mean tidal range exceeds 3.5 m, offers a potential of $\sim$10 GWh km^{-2} y^{-1} (Table 5). But, considering the coastal morphology, this area may not be suitable for the construction of barrages. The limestone rock formations of the northern Mozambique–Tanzanian coast provide more suitable conditions for barrages, but potential environmental effects of modifying tidal regimes in sensitive environments may restrict possible developments to micro-scale barrages. The low temporal availability of power (Table 5) impedes the usefulness of tidal barrages in decentralized grids.

4.4. Tidal current turbines in the WIO

Only two locations with high potential (MSS $\geq$2 m s^{-1}) for tidal current turbines were identified (Tanzania–Zanzibar and Kenya, Fig. 3, Table 6). Strong tidal currents have also been reported, but not verified by measurements, at Montepuez Bay (Mozambique) and Pemba Island (Zanzibar). Another four locations with conditional potential for tidal current turbines were found along the Mozambican and Tanzanian coasts. The amount of energy that can be converted by tidal current turbines of different sizes, at each of the identified sites, is given in Table 6. Based on available data, the potential for tidal current turbines in

Table 5
Mean tidal range, annual energy output, and temporal availability of power (% of time) for locations in the WIO with a mean tidal range above 2.4 m. Calculations are based on optimization in respect to energy output, at the cost of temporal availability.

Region	Location	Mean range	One-way operation		Two-way operation	
		m	MWh km^{-2}	%	MWh km^{-2}	%
Central Mozambique	Beira	3.58	6278	32	10 358	44
Central Mozambique	Quelimane	2.60	2809	30	4919	33
Central Mozambique	Pebane	2.52	2777	30	4858	33
Central Mozambique	Angoche	2.40	2895	30	5060	33
Northern Mozambique	Moçimboa da Praia	2.60	2885	31	5055	36
Western Madagascar	Nosy Chesterfield	2.60	2862	30	5004	33

Table 6
Maximum spring speed (MSS), site depth, quality of data (H = high quality, current measured in midwater, I = intermediate quality, current measured close to bottom, extrapolated to midwater, L = low quality, current measured at surface), annual energy output, and power availability as percentage of time for tidal current turbines at locations in the WIO with tidal currents $\geq$1.5 m s^{-1}. Energy output is calculated per one (1) device of specific dimensions corresponding to small, and micro tidal current turbines at sites where depth allows for deploying the devices.

Region	Location	MSS	Depth	Quality	Small		Micro	
		m s^{-1}	m		MWh	%	MWh	%
Kenya	Watamu	2.5	6	H	89	74	46	82
Tanzania–Zanzibar	Kunduchi	4.5	–	L	–	–	114	90
Tanzania–Zanzibar	Mbudya	1.5	15	H	19	53	10	69
Tanzania–Zanzibar	Dar es Salaam	1.8	7	L	34	63	18	74
Central Mozambique	Bazaruto Island	1.5	23	I	19	53	10	69
Southern Mozambique	Inhaca Island	1.5	10	H	19	53	10	69

the WIO seems limited, but unrevealed locations with strong currents may exist.

4.5. Ocean current power in the WIO

The most fast-flowing ocean currents that pass through the WIO are the Somali Current and the East African Current, which are strongest during the southern monsoon, and the Mozambique Current which is strongest during the northern monsoon. During the southern monsoon, current speeds have been reported to reach extreme 3.5 m s^{-1} off the Somali coast [117], and to average 2 m s^{-1} at Zanzibar [118]. More restrictively, the historical ship drift from Cutler and Swallow [106] rendered mean/maximum speeds of 1.2/1.9 m s^{-1} for the Kenyan coast, and 0.7/1.5 m s^{-1} for Tanzania–Zanzibar, respectively (Fig. 3, Table 7). Further, mean speed mean speeds of 1–1.5 m s^{-1} and maximum speeds above 2 m s^{-1} have been reported for the northern coast of Mozambique [104]. Here, the historical ship drift indicated northern monsoon mean/maximum speeds of 0.9/1.4 m s^{-1}.

On the basis of these results, Kenya (northern latitudes) and Northern Mozambique (southern latitudes) may have at least conditional potential for ocean current power. The continental shelf is very narrow in both areas which indicates that the strong currents sweep close to shore, which is necessary for energy extraction. Hitherto, the ocean current power technologies are in early development stages; as a brief indication though, a small ocean current power device would generate approximately 160 and 370 MWh per unit and month in continuous currents of 1.4 and 1.6 m s^{-1}, respectively.

Table 7
Coastal surface current speed (m s^{-1}) based on ship drift records in regions of WIO. For ship drift data [106], mean speed has been calculated as the mean of all reporting during November–April and May–October (1854–1974), for northern and southern monsoons respectively. Maximum speed is based on year-averaged 10-day periods.

Region	Northern monsoon		Southern monsoon	
	Mean	Max	Mean	Max
Cutler and Swallow [106]				
Kenya	0.7	1.5	1.2	1.9
Tanzania – Zanzibar	0.7	1.5	0.7	1.4
Southern Tanzania	0.4	0.7	0.8	1.3
Northern Mozambique	0.9	1.4	0.6	1.1
Eastern Madagascar	0.5	1.2	0.8	1.4
Southern Madagascar	0.7	1.1	0.6	1.3
DiMarco [104]				
Northern Mozambique	1–1.5	> 2		

4.6. Outlook: the results in perspective

Table 8 provides a summary of the results for each WIO region, showing that there is a substantial resource-based potential for ocean energy in the WIO. Some examples of how the ocean energy potential matches with current energy supply and solar and wind resources are discussed below.

About half of the small population of the Comoros currently have access to electricity. About 90% of the ~5 MW capacity is generated from imported fossil fuel [5,109]. The resource potential for OTEC is rated high, with several locations where sufficient ΔT is available close to shore. A single small-sized OTEC plant of 10 MW would cover several times the current electricity consumption of 20 GWh y^{-1}. The insolation is also high and might be utilized for boosting the capacity of OTEC. While OTEC and insolation both peak during the northern monsoon, the wind power potential peaks during the southern monsoon (wind speed means above 5.5 m s^{-1}). The situation is comparable at the nearby Mayotte (France) where the economic situation may allow for taking a lead on development. However, the relatively high occurrence of tropical cyclones in this region is an important factor, which may discourage the use of exposed devices.

The remote islands of Réunion and Mauritius have already shown particular interest in exploring the opportunities of ocean energy [10,113]. The electric grids have full coverage, and new power sources are needed to substitute the substantial fossil fuel imports [112,113]. Both Réunion and Mauritius have high resource-based potentials for wave power, wind power, OTEC, and solar power. The former two peak during the southern monsoon while the latter two peak during the northern monsoon, which represents a prolific combination. Although the islands endure the risk of devastating tropical cyclones that could be problematic for offshore installations Réunion has advanced plans on installing both wave power and OTEC within the next few years [10].

The population of the Seychelles is small and scattered over a multitude of remote islands. The electrification level is near 100% but is totally dependent on fossil fuel. The extraordinary annual oil imports of 30 barrels per capita, may be a strong incentive for increased use of RES [5,108]. The potential for solar PV is high year round. The potentials for wind and wave power were ranked

Table 8
Summary of results as the highest rank of resource-based potential for ocean energy, solar PV, and wind power for each region. H indicates 'high' resource potential and C indicates 'conditional' resource potential (see Table 1). Note that ranks may be based on single sites, not necessarily representative for the whole region. All ranking is based on annual averages; peak seasons are indicated in brackets where (S) is southern monsoon (Nov–Apr) and (N) is northern monsoon (May–Oct). Empty cells (–) indicate low potential. The main current electricity supplies are indicated. WP = wave power, OTEC = ocean thermal energy conversion, TB = tidal barrages, TCT = tidal current turbines, OCP = ocean current power.

Region	WP	OTEC	TB	TCT	OCP	Solar PV	Wind power	Current supply
Kenya	–	–	–	H	C (S)	C (N)	C (S)	Hydro, oil, RES
Seychelles	C (S)	H (N)	–	–	–	H (N)	C (S)	Oil
Tanzania–Zanzibar	–	–	–	H	–	H (N)	C (S)	Hydro, coal, gas, oil
Southern Tanzania	–	C (N)	–	–	–	C (N)	C (S)	Hydro, coal, gas, oil
Comoros and Mayotte	–	H (N)	–	–	–	H (N)	C (S)	Oil
Northern Mozambique	–	H (N)	C	H	C (N)	C (N)	C (S)	Hydro, coal, oil
Central Mozambique	–	–	C	C	–	H (N)	C	Hydro, coal, gas, oil
Southern Mozambique	H (S)	–	–	C	–	C (N)	C	Hydro, coal, oil
Western Madagascar	H (S)	–	C	–	–	H	C (S)	Hydro, coal, oil
Eastern Madagascar	–	C (N)	–	–	–	H (N)	H (S)	Hydro, coal, oil
Southern Madagascar	H (S)	C (N)	–	–	–	H (N)	C (S)	Hydro, coal, oil
Réunion	H (S)	H (N)	–	–	–	H (N)	H (S)	Coal, hydro, oil, biomass
Mauritius	H (S)	H (N)	–	–	–	H (N)	H (S)	Coal, oil, biomass

as conditional on an annual basis, but are high during the northern monsoon. Under the particular circumstances of fossil fuel dependence, all three energy sources are likely to become useful for future energy supply in the Seychelles. Wind power has the advantage of being a well-proven technology and is more easily maintained than wave power. The low temporal variability and higher predictability of wave power, improved by the oceanic-swell-dominated conditions in the Seychelles, may come to motivate the use of this technology at particular locations. As shown by [22] the prevailing wave power levels are enough to desalinate large amounts of water. By contrast, the high potential for OTEC in the Seychelles is not likely to be of interest due to the small populations on the islands.

In Madagascar, the energy sector is undeveloped with only about 10–15% [3] of the rural population having access to electricity. However, Madagascar also has huge unexploited resources of hydropower and recent findings of fossil fuel [110]. The high resource potential for wave power and solar PV may consequently be of low interest, but of possible use for remote area electrification/desalination purposes. Tropical cyclones pose a potential hindrance throughout Madagascar's coast, not least for wave power.

Mozambique has an extremely low electrification level (2–3% in rural areas [3]), but has a good supply of inexpensive hydropower to the national electric grid [111]. The high resource-based potential for wave power in southern parts of the country may possibly be of interest for remote area electrification or desalination and irrigation. The wind power potential is fairly low in coastal areas of Mozambique, but solar PV may be a good complement.

Northern Mozambique has a high resource-based potential for OTEC. As the national electricity grid is supplied only from geographically distant generation, the predictability and continuity of OTEC may suit the purpose of stabilizing the national grid in the northern part of the country. Moreover, the tidal range is at levels which were considered valuable for tidal barrage developments in a recent resource assessment for China [67]. However, parts the region also have unexploited hydropower resources which are likely to be more cost-efficient to utilize. It should also be noted that the region is known to contain particularly valuable and sensitive marine ecosystems.

The potential for ocean energy seems limited for Kenya and Tanzania. A few sites of high potential for tidal current turbines were identified but it is doubtful whether these are enough for creating interest in the technology. However, both countries have scarcity not only of electricity but also potable water and it should be noted that the wave power levels in Kenya might be sufficient for desalination and irrigation, as suggested by [22], while further inventories of the OTEC potential might be motivated for southern Tanzania.

In conclusion, the ocean energy resources of the WIO are substantial and may provide propitious future opportunities for the developing power sectors of the region. However, the resource availability must be met by the need for energy, to be of any interest. According to the findings of this study, such a match may be found in the small island states of the WIO in general, and possibly in some remote areas of the African mainland. Ocean energy has already been taken into consideration in the region [10], but if more than a few isolated projects are to be realized, efforts towards successful technology transfer, further deliberated by Karakosta et el. [119], have to be undertaken. Finally, for the RES potential to be safely exploited uncertainties regarding environmental impacts need further consideration.

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